to their competitor. If the Commission attempted to prevent such sharing by prohibiting reselling or sharing of base stations, it would also tend to preclude efficient, market-driven sharing arrangements.[34] In principle, one could also imagine similar problems with frequency division sharing. Indeed, the FCC has had to develop rules, such as emission masks and modulation limits, to insure that licensees stay within their assigned bandwidth. However, the laws of physics help here since most installed radio systems have the characteristic that their bandwidth cannot be changed easily and costlessly. Consequently, frequency division sharing does not create the harmful incentives discussed above.

A second reasonable sharing policy is one based upon a token-passing protocol. Each licensee has a maximum permitted channel occupancy time (say one second) but, if all transmissions are accommodated before the time expires, the licensee signals the next operator in line that the channel is available. Such a sharing policy has the theoretical advantage that it passes the channel out accurately in response to customer demand. But, this policy also creates incentive problems. If firms A and B compete, why should A pass the channel on to B, allowing B to increase capacity and improve service? Wouldn't A's incentives be better served if it kept the channel (say using it to cycle through all customer transponders in order to "continuously verify the proper working of all their hardware") rather than passing the channel on to a competitor? Such token-passing protocols can work well for sharing resources inside organizations under a common goal or under common management. But, they were not designed for allocating resources among competitors and should not be expected to work in that situation.

Incentives to innovate are stifled under time-division. Some innovations (e.g. the low-power long-pulse mobile unit) cannot operate in the time-division environment. Other

[34] For example, AM stations WSBC, WCRW and WEDC operate on 1240 kHz in Chicago under a time sharing arrangement. (All three stations were licensed before the creation of the Federal Radio Commission.) WCRW and WEDC share a single tower. See, Broadcasting & Cable Yearbook 1993, page B-106.

innovations (e.g. a better base station or a cellular reuse mechanism) would free up capacity only for the lion's share to be divided among a firm's competitors.

Incentives to remedy faults would be reduced. For example, a mobile transmitter that fails by transmitting continuously (stuck on) will degrade the operation of all nearby base stations. But, if a firm is one of three operating in a band, it receives only one third of the harm, its competitors receive the other two-thirds.

All in all, time-division multiplexing would thoroughly pervert incentives. Incentives to do bad things, such as create sham competitors, would be created. Incentives to do good things, such as innovate or provide reliable mobile equipment, would be weakened or abolished.

4. The FCC Enforcement Burden

Any time-division sharing system will put a substantial enforcement burden on the FCC. For example, the FCC will have to decide if new entrants are real or sham. If time-slots are divided on a criterion other than equal shares to each firm (say in proportion to customers or sales), then the Commission will find it necessary to verify system loading. If a dynamic sharing system, such as token passing is used, the Commission will have to establish mechanisms to verify that all participants in the market are following the rules. None of these tasks are easy. This regulatory system is far from self-enforcing. Complex rules will be hard to devise and hard to enforce. But weak rules lead to interference and loss of service to the public.

5. Conclusions

Time-division sharing of LMS bands appears ill-advised. When the FCC chose to license two cellular providers in each market using frequency division techniques, it recognized that this policy choice created competition at the expense of a 10-15 percent increase in network infrastructure costs.[35] In contrast, time-division sharing of LMS bands would increase costs by more than 100 % when adding a second firm in a band. Time-division sharing would limit important technical alternatives. Any of the firms sharing a band could costlessly expand capacity to fill the band, creating incentives against technical innovation and for cheating.

B. Frequency Division Multiplexing

Radio regulators often use frequency division to separate multiple licensees in the same geographic area. Because frequency division fits well the laws of physics, enforcement costs are reasonable. Indeed, the current AVM rules (47 CFR 90.239) do exactly that with two separate eight MHz AVM bands. Splitting the spectrum into smaller subbands may create efficiency losses due to losses in efficient scale. For example, it is commonly accepted that combing multiple land mobile channels to permit operation of trunked

C. Higher Power Pulses

If a firm operating a pulse-ranging system observes that it is suffering from interference, it can reduce the effects of such interference by transmitting higher power signals. Increasing the ratio of the power in the desired signal to the combined power of the interference and noise[36] can be accomplished in several ways. Perhaps the most straightforward way to do this is to increase the transmitted power. If the mobile unit transmits twice as much power, then the ratio is increased by a factor of two.

Transmitting at higher powers would require an existing operator to replace all the mobile units (or at any rate all the mobile units operating in the affected area) with units capable of operating at higher power. Doing so is a very substantial and expensive task. Not only must new vehicular units be purchased to replace the existing units, but many users must bring their vehicles in for this replacement. Thus, in addition to the cost of the vehicular unit and of its installation, there is a significant cost imposed on the consuming public.

The mobile radio units with the capacity to transmit at higher power will be more expensive than lower power units, and battery operation may be more restricted or impossible at the higher power levels.

Although this solution may be a temporary palliative (achieved at the expense of increasing interference to the other cochannel pulse-ranging systems), a game of escalation should be expected to begin. One would expect the operators of the other cochannel pulse-ranging systems to also increase their power and thereby eliminate the advantages of this approach. Raising the power of any one system would increase

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[36] This is the normal signal-to-noise ratio (SNR) or signal-to-noise and interference ratio (S/(N+I)) that communications engineers normally use. We are being careful in our terminology for two reasons — this is a pulse system and we are considering both noise and interference.

interference into other systems and operators of those systems could be expected to try to compensate.

Finally, notice that this approach does little to remove the uncertainty associated with interference from cochannel systems. Raising power by 3 dB or even by 10 dB will not provide any assurance that the operator of a cochannel LMS system will not install a base station near an existing base station and thereby create substantial interference and disruption to system operations. We saw in section IV above that a cochannel pulse-ranging base station located in the same community would raise the noise floor by 30 to 60 dB.

There are practical limits to this approach. Current cellular mobile and portable radios operate with powers ranging from about 600 milliwatts (cellular portables) to 4 watts. Some mobile radios operate at higher powers — up to about 20 to 40 watts. But, as power levels are increased, it becomes more difficult and expensive to build a radio system. Similarly, as the signal-to-noise ratio decreases, acquisition of the signals becomes more difficult. Our model implicitly assumes no such problem.

Finally, we reach the upper legal limit of power increases because the FCC rules limit pulse-ranging systems to powers of 1,000 watts.

D. Longer Measurement Time

Another way to cope with interference is to measure the pulse arrival over a longer time. The Cramér-Rao bound shows that doubling the duration of the pulses cancels out a 3 dB increase in the noise floor. Of course, in order to do this, the equipment must be modified to transmit longer pulses. As with increasing the power, such a major modification to the entire system architecture of an existing system is expensive and difficult.

An additional major drawback of increasing measurement time is that doing so decreases capacity. Thus, it might be a useful technique for protecting against cochannel interference in isolated smaller cities, but the loss of capacity argues against using this technique in more built-up areas. This technique is inefficient — at the expense of cutting the capacity in half one can only reduce the effects of an interfering signal by 3 dB.

And, as with the power increases, there is the possibility of an escalation scenario. Suppose that there are two firms, **Larry's Locations** and **Positive Positions**, sharing a band in a city. Larry notices interference and responds to that interference by doubling the duration of the location pulses. His system improves slightly, but now he is transmitting twice as much interfering energy. Positive Positions responds by increasing the duration of their pulses. Now interference is worse than ever and, in addition, capacity has fallen.

Furthermore, as with several other interference alleviation techniques discussed above, this approach offers no guarantee that it will work — substantial uncertainty about possible future interference will remain after increasing the duration of transmissions.

E. Additional Bandwidth

Another approach to coping with noise is to increase the bandwidth for each licensee. Of course, this alternative immediately runs into practical problems because additional bandwidth is not readily available. But, if it were, it could be used to combat added noise. The Cramér-Rao bound shows that doubling the bandwidth cancels out a fourfold increase in noise power.

From a practical point of view using such extra bandwidth would be difficult and disruptive. It first requires redesign of essentially the entire radio side of the system and then the replacement of all the mobile units and fixed receivers. This bandwidth expansion is exactly the place where spread-spectrum techniques can be used in LMS systems. Spread-spectrum techniques allow the creation of pulses with wide bandwidth and sufficiently high pulse power to function efficiently. Spread spectrum techniques permit the generation of long pulses that permit highly accurate measurement of time-of-arrival because of the sharp peaks in their autocorrelation functions.

An interesting exercise is to ask how much additional bandwidth would be required to counteract the effects of the interference from a cochannel LMS operator. Recall, that in Section IV we showed that, under relatively benign assumptions a cochannel LMS system increased the interfering power by 34 dB.[37] The Cramér-Rao bound on the performance of time-of-arrival measurements shows that doubling the bandwidth compensates for a four-fold increase in signal-to-noise ratio. Expanding the bandwidth by a factor of 50 (17 dB), from 8 megahertz to 400 megahertz, will cancel interference in this benign scenario. Of course, if the interfering transmitter moves closer than 10 miles away, more bandwidth expansion would be required to compensate for the increased interference.

Another way to look at this result is to observe that two cochannel systems operating in 400 MHz and generating sufficient interference with one another to raise the noise floor by 34 dB will have the same capacity[38] as two systems operating in 16 MHz and using frequency division multiplexing to divide the spectrum. This may explain why the FCC's 1974 order set up a regulatory environment with two subbands.

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[37] We assume that the current noise level is -90 dBmW (middle of the observed range today) and that the cochannel base station is ten miles away.

[38] Again, this conclusion may be over optimistic — two real world systems might not be able to share 400 MHz. For the conclusion to be true, the conditions necessary for the application of the Cramér-Rao bound must hold. In fact, as interference increases it may become impossible to maintain system synchronization, to address the mobile units, or to acquire the signal. But, the Cramér-Rao bound shows that we can do no better than shown in this discussion.

directional antenna systems are possible. One, the traditional high-gain receiving antenna, concentrates high gain towards the desired transmitter while attenuating interfering signals from all other directions. The other, the nulling antenna, directs high

A directional antenna solution that nulls out interference coming from a known location (e.g., a fixed station of the cochannel LMS system) would appear more feasible since the antenna array would not need to be repointed rapidly. Such directional antennas would not cope with interference from the mobile units of the cochannel system. Notice that this approach is conceptually quite similar to subtracting a transmitted reference signal from the cochannel base station. Although using a transmitted reference signal has the disadvantage of requiring a separate communications link, that approach does not create the coverage holes that would be created with use of a directional antenna to null out cochannel base stations.

We must conclude that, at this time, directional antennas do not appear to offer a practical or cost-effective palliative measure for coping with the high levels of interference from a cochannel pulse-ranging system. In some circumstances, however, directional antennas may be helpful. And, again, we must note that, as with all the other palliative solutions, the system operator continues to face uncertainty about the future effects of interference from a cochannel system.

Noise blanking techniques are more promising.[40] It should be relatively easy to detect the presence of short, high-power interfering signals such as radar pulses. The receiving system could then use its knowledge of the presence of such interference to discard measurements made while the interfering pulse was present. If the interfering pulses are short and have a low duty cycle, then this approach to interference suppression can be expected to work reasonably well. The costs should be primarily one-time design costs and the loss of capacity should be minor — roughly speaking it could be expected to be the same order of magnitude as the duty cycle of the pulses. Notice that this technique might be useful for reducing the effect of microsecond-long radar pulses interfering with

[40] See the discussion of noise limiting and blanking techniques in chapter 9 of *Communications Receivers Principles and Design*, by Ulrich L. Rohde and T.T.N. Bucher, McGraw-Hill, 1988.

a pulse-ranging system using millisecond-long pulses. It could not cope with interference between two pulse-ranging systems using pulses of approximately the same duration.

G. More Receive Sites

Increasing the number of receive sites in the fixed network of the LMS system provides another way to combat interference. For example, under assumptions favorable to this technique, doubling the number of receive sites improves performance of a single time-of-arrival measurement against noise and interference by a factor of 6 dB.[41] Under less favorable assumptions the gain is smaller or nonexistent. For example, if base stations transmit to mobiles in a simulcasting fashion, then the proliferation of base stations would result in an increase in transmitted energy and interference. Under such circumstances, increasing the number of fixed sites leads to another escalation scenario.

This is an extremely expensive approach to combatting interference. Receive sites are expensive elements of the system. Doubling the number of receive sites roughly doubles the cost of the fixed network of the pulse-ranging system. Additionally, there is the problem of obtaining acceptable sites. Locating receive sites in parks or residential neighborhoods can be difficult or impossible.

This technique copes best against a geographically uniform growth in the noise floor, such as would be produced by a single high-power interference source located on a mountain several miles outside of town or uniformly distributed low-power transmitters. It does not solve the problems created by a single high-power interference source located in the middle of the LMS service area.

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[41] This calculation assumes that the propagation from the mobiles is governed by an R^4 law and that increasing the number of receive sites has no impact on the interfering power level.

As with the other technical palliatives uncertainty about future interference from the cochannel system operator remains after this technique is used.

H. Geographic Separation of Cochannel Separation

Geographic separation between pulse-ranging systems permits the interfering signals to be attenuated by distance and the blocking effects of terrain and other obstructions. Such geographic separation is commonly used in radio regulation[42] and requires no elaboration.

This is the simplest method to implement. If the cochannel separation is sufficiently large, then this option provides a high degree of assurance against unwanted interference from other LMS systems. The biggest benefit of this approach when compared to all others is that it leaves LMS system operators with the least uncertainty regarding potential interference from other LMS systems. There are essentially no technical costs to this solution. There will be a region between systems that suffers from degraded region or is even left uncovered (a buffer zone) and although interference will be attractive. Similarly, there are practical limits to the pulse duration — the pulse should be short enough that a car doesn't move very far during the pulse.

Comparison of the Cost of Interference Reduction Techniques For Coping with Collocated, Cochannel LMS Systems		
Technique	**Cost to compensate for a 60 dB increase in noise floor caused by a cochannel system**	**Cost to compensate for a 40 dB increase in noise floor caused by a cochannel system**
Higher power pulses	Infeasible	Probably infeasible. A one watt pulse would become a 10,000 watt pulse. The mobile unit would become much larger and would cost in the tens of thousands of dollars.
Longer pulses	Capacity drops by a million-fold. The one customer's vehicle can drive 10 miles during a single measurement interval. Practically speaking, the system is no longer useful for locating moving vehicles.	System capacity drops by ten thousand-fold — say from one million vehicles to one hundred.
Additional bandwidth	8 GHz required	800 MHz required
Noise canceler or Directional receiving Antennas	Infeasible at present	Infeasible at present
Additional receive sites	Thousand-fold increase in receive sites required. If fixed network cost $5/mobile per month, it now costs $5,000/mobile.	About hundred-fold increase in sites required — raising a fixed infrastructure cost of $5/mobile/month to $500/mobile/month.

X. Conclusions

If two pulse-ranging systems operate in the same band in the same city at the same time (under either the FCC's current rules or the proposed rules) using a modern, reasonable design each will generate intolerable interference into the other. This is not a case of mild interference which can be remedied by slight improvements in the system. Rather, cochannel systems generate enormous levels of interference which fatally burden the system receiving the interference. If minor interference can be compared to a chipped coffee-cup — an inconvenience but you can still use the cup for your coffee — then the interference in this case compares to a cup that has been smashed into dozens of pieces — there is no way one can take a drink.

Of the many techniques for permitting multiple LMS systems to share the spectrum a regulatory system modelled on traditional radio regulation using separate bands and geographic separation of cochannel systems offers the highest chances for regulatory success. Time-division sharing techniques, in addition to having significant efficiency burdens, create substantial enforcement burdens.

VITAE

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Elected to Executive Committee IEEE Washington Section, (1973-74)

Elected to Executive Committee IEEE Northern Virginia Section (1983-1985)

General Chairman, Third Data Communication Symposium (IEEE/ACM)

Chairman, Technical Committee on Societal Implications of Technology. (IEEE), 1984

Chairman, Professional Group on Information Theory, Metropolitan Section, (1971-72)

Member, Association for Computing Machinery (ACM)

Conference Board IEEE Communications Society (1980-83)

Member, Mathematical Association of America

Member, Commission C, URSI; U.S. delegate to XXth Congress

Delegate, National Research Council, National Academy of Science

Scientific Advisory Board, Institut National Researches de la Scientifique, Quebec, Canada, (1992 -).

International Advisory Committee, TENCON, Melbourne, Australia, (1992).

Advisory Committee, International Symposium on Personal Communications, Nanjing, China, 1993.

Editorships:

Editor, IEEE Transactions on Communications for Computer Communications (1972-76).

Associate Editor, Journal of Telecommunications Networks, (1981-1986).

Editor, Series of Communications and Signal Processing, Computer Science Press, Potomac, MD, (1981-).

Guest Editor, IEEE Transactions Special Issue on Computer Communications, Jan., 1977.

Guest Editor, IEEE Transactions Special Issue on Military Communications, Sept. 1980.

Guest Editor, IEEE Network, Special Issue on Network Security, April 1987.

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Guest Editor, IEEE Journal of Selected Areas of Communications, Special Issue on Secure Communications, 1989.

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